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The Generation of Situational Awareness within Autonomous Systems – A Near to Mid Term Study – Issues

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ABSTRACT

This study aims to clarify and capture the nature of electronic situational awareness and its interface with electro/mechanical systems. It argues that "autonomous situation awareness" is about the sufficiency of awareness for autonomy in the situation at hand. The approach is calibrated through historical case studies, and the study then considers the potential from near to mid term technology.

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The Generation of Situational Awareness within Autonomous Systems – A Near to Mid Term Study – Issues

Executive Summary

The aim of this document is to clarify and capture the nature of electronic situational awareness and its interface with electro/mechanical systems. This interface is critical in the construction of autonomous systems (robots) with the capacity to perceive their environments, to process that perception and to physically act on the results. This document thus aims to clarify issues, and hence improve the understanding of whether and how autonomous systems could impact upon warfighting.

The core theme of this paper is that *autonomous situation awareness* can be considered through the continuums of:

1. *Autonomy*, measured by the time between references to a human being for input.
2. *Awareness*, measured by the system's usage of information about its environment. Importantly, the system will only use a subset of the total information available.
3. *Situation*, driven primarily by the severity of consequences of the system making decisions and taking action. Severity of consequences is the critical link to the human decision to employ the autonomous system.

The central result is that it is not a question of whether a system "is" autonomous or "has" awareness, but whether the system has *sufficient* awareness to be *sufficiently* autonomous for the situation at hand. Historical review identified cases where "dumb" technologies with low awareness had been deployed at high autonomy, while "smart" technologies with high awareness had been held at low autonomy. Historical experience also suggests strong precedents for concept development, notably from mine warfare, beyond visual range combat and mission command.

In the near to medium term future, fundamental delays in communications (line of sight, speed of light) will force certain systems to higher autonomy. However, if the delay is acceptably low, "human virtual presence" with lower autonomy may be preferred. While it is unlikely that technology will be sufficient if raw data flows are used, the volume and rate of data may be manageable given compression and simulation matched to human perception. Mobile phone networks might be used, given sufficient assurance.

Also in the near to medium term future, smart materials and grid computing may ease the problem of monitoring robot status. However, for movement in the physical environment and interaction with other entities, robot utility will be bounded by the capacity to simplify the environment (by either physical or information means), and by the demand for integration into total battlespace management (deconfliction).

Moreover, for mobility in complex terrain, robot system designers are still seeking workable processes for mapbuilding, with enduring problems that either require heuristic insights or intrinsically parallel computing (DNA or quantum computing).

In strategic terms, given the precedents in concept development, and the known bottlenecks and progress in technology, robotics has *passed* the point of being a new strategic threat, to one that *broadens* the threat at the operational and tactical level. The key feature is *comodification*, enabling different actors to utilise formerly-specialised technology. The threat space from autonomous systems thus builds on advances and comodification of enabling technologies, notably including: insertion into space/orbit, civilian communication networks, and computer hardware and software.

Technology advances aside, this study noted potential assumptions about the human agencies employing robots. The options for robot use are shaped by social background (casualty aversion), expected environment (expeditionary forces) and tempo of decisions (combat intensity). It is to be emphasised that low technology, low awareness robots have already been deployed at high autonomy in the past, and could well be used again.

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Patrick Hew joined DSTO in 2000, having gained a PhD in Mathematics and Intelligent Information Processing Systems from The University of Western Australia. His first work was in support of HQAST and NORCOM-Coastwatch, in the analysis of maritime surveillance operations and developing concepts for command support tools. In 2002, Patrick relocated to the DSTO team embedded in Australian Defence Headquarters, providing advice on capability development, force structure and the implications of future technology and environments. Since then he has led and conducted work including future technology analysis for AIR7000, thinking in support of the Future Strategic Environment, and the Amphibious Task Group 2005 cross-capability study.

Contents

Glossary

GPS	Global Positioning System
ISTAR	Intelligence, Surveillance, Target Acquisition & Reconnaissance.
UAV	Uninhabited Aerial Vehicle.

1. Introduction

> "The limiting factor … is not the technology, but the bureaucracy – getting the necessary permission to engage a target."
>
> – Attributed to Frank Pace, executive vice president of General Atomics Aeronautical Systems Inc (the manufacturer of the Predator UAV) [1].

The advance of robotics technology has been identified as a driver, potentially a disruptive driver, to future warfighting. The particular aspect of *autonomous situation* awareness is critical to robotics, in the development of systems that can perceive their environments, process that perception and physically act on the results.

Aim

The aim of this document is to identify and discuss key issues concerning autonomous situation awareness, and their potential influence on warfighting and security thinking.

Level

This document is aimed at Defence staff in strategy and capability development.

Scope

This document is concerned with issues and insights. The underlying analysis may be found in the supporting technical report [2].

2. Discussion

Human-Robot Systems Thinking

1. *Autonomy, awareness and situation may be regarded as linked but independent continuums.*

   Autonomy can be quantified as the time between references to a human being for input. *Awareness* can be quantified robot's usage of information about its environment. This is only part of "situation awareness", where *situation* is primarily about the severity of consequences from robot actions.

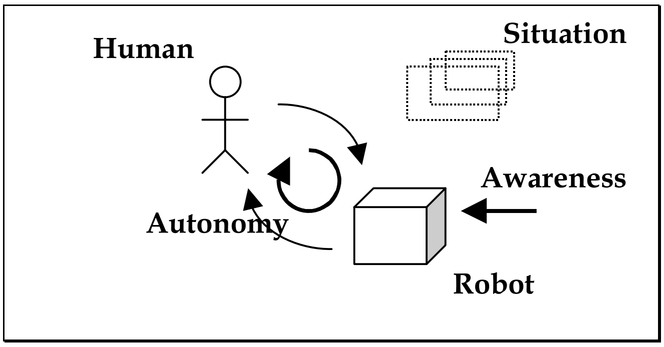

Figure 1: Autonomy, Awareness and Situation.

   As a result, it is not a question of whether a given robot "is" or "is not" autonomous or aware. The continuum of *autonomy* ranges from "remote control" through "human in loop" to "fire and forget" (Table 1). The continuum of *awareness* handles "dumb", "smart" and "brilliant" systems (Table 2). Their combined utility to a *situation* is a separate question, the critical one, leading to the next point.

2. *The utility of robotics technology (for autonomy and awareness) cannot be assessed without an understanding of the robot's environment (its situation).*

   The study of "autonomous situation awareness" was triggered by the following question: Given a robot system from today, what is the potential effect of upgrading its systems with future technology? The best answer is that this question is meaningless. Examples from historical and contemporary use show that increased technology need not imply greater utility; indeed, that "low technology" robots have been deemed useful in the past while their "high technology" descendants are unacceptable today.

   The point about utility over time also holds across space. The physics of sensors and effectors (mechanical, electromagnetic, optical, acoustic, chemical) apply universally across physical space (aerospace, maritime, land/littoral). The logic of data processing applies universally sits independently in information space. The overall utility sits, however, in the social space of effects and consequences.

   The overall result, therefore, is that any assessment of technological sufficiency of a robot needs to be coupled to assessments of the complexity of the environment and the severity of consequences. This would entail a social analysis of the consequences of robot failure(s), with corresponding acceptability within its socio-political political environment. The question then is about how such analysis (concept development), to include this inherently human dimension of *situation*, can be approached.

Table 1: Spectrum of Autonomy – Examples.

"Find-Replace" in a document editor.	< 5 seconds.	The user specifies (*deploy*) some text to Find and Replace, and the robot verifies with the user at each instance (*refer*).
Mars Exploration rovers.	> 20 minutes (average).	Communication from Earth to Mars has an unavoidable delay, limited by the speed of light. The robot must be autonomous within this communications loop.
Hubble Space Telescope	> 1 hour.	The particular case of entering *safemode*. Safemode is a programmed response to an unknown (and potentially dangerous) condition. The robot reverts to a known "safe" mode, and calls for human help. Early in its career, Hubble suffered multiple entries into safemode.
"Replace All" in a document editor.	∞	Once the user has specified the text to Find and Replace, the robot can proceed with*out* referencing back.
Land Mine	∞	Once a land mine is deployed, it will explode if triggered, without referencing back to the human who placed it.

Table 2: Spectrum of Awareness – Examples.

Land Mine	1 bit (On/Off)	Physical pressure pad, in "not pressed" or "pressed" state.
V-1 Flying Bomb	Bytes	Azimuth preset by launch ramp, held constant by weighted pendulum and gyro-magnetic compass. Range embedded in a propeller-like anemometer completing a set number of rotations.
GPS Tomahawk missile.	Kilobytes	Sequences of waypoints for navigation.
Aegis Weapon System	Megabytes	Radar tracks, assembled across a naval task force.
Joint Air-to-Surface Standoff Munition	Gigabytes	Imaging infrared seeker, pattern matching on targets.

Case Studies – Land Mine and Aegis Air Warfare System (Table 3)

The land mine and the Aegis air warfare systems show that (future) robotics technology cannot be assessed without an understanding of the (future) environment. Notable points:

- Both systems can be released to infinite autonomy; that is, to act without referring back to a human.
- The low-technology land mine was fully sufficient for the situation of 1917, of open warfare in open terrain. In comparison, the high-technology Aegis is not regarded as sufficient for 2004, for "Auto Special" operations in littoral airspace crowded with civilians.
- Equally too, (anti-personnel) land mine technology is unacceptable post-1997, for conventional military forces of nations signatory to the Ottawa Convention. Other actors, however, may not feel so restricted.

Table 3: Case Studies - Land Mine and Aegis Air Warfare System.

System	Autonomy	Awareness	Situation	Tech Sufficient?
Land Mine.	∞ (When armed by soldier.)	1 bit. (Pressure pad).	1917 World War I.	Yes. (Combat use.)
			1997 Conventional military forces.	No. (Signatories to the Ottawa Convention.)
Aegis.	∞ (When set to "Auto Special" by ship captain.)	Megabytes. (Radar tracks.)	1984 Blue-water combat, mass Backfire raids.	Yes. (Deployed but not combat tested.)
			2004 Littoral combat, peacekeeping.	No. (Vincennes incident.)

Precedents for Concept Development

3. *Mine Warfare.*

   Any system that links sensor to shooter and releases lethal effect without reference to a human is equivalent, technologically, to the simple, pressure-activated mine. To the objection that "mines are indiscriminate" against more advanced systems, the argument is that "indiscriminate" is just a point on the continuum of awareness.

   The use of mines is governed and restricted by international law and agreement, so future robot systems may similarly be restricted. Equally too, the historical point that mines can and have been disarmed, lifted and turned against their original owners has implications for robot tactics and doctrine development. On the positive side, concept development can draw upon the known strengths of mine warfare: the capacity to engage at tempos faster than human reaction, and thus the deterrence/denial of battlespace volumes.

4. *Beyond Visual Range Combat.*

   For human beings, beyond-visual-range combat is qualitatively different to within-visual range combat, for it requires machine sensor data to be assimilated by human sensors to yield cognitive awareness. For robots, however, no such distinction exists – it is all just data from sensors. The historical issues that have restricted the use of long-range weapons could thus impact on concepts for using robots.

5. *Mission Command.*

   The question of whether a robot can be used in a given application is at least as difficult as that faced by a commander in delegating – providing autonomy – to a subordinate. The body of knowledge in mission command is thus of potential utility.

   Moreover, while replacing the human by a robot in physical space appears to be unequivocally desirable, it is by no means clear that this is true in the information or social spaces, or that overall robot effectiveness improves. Comparison and trade-offs can be made between robot "smart thinking" (autonomy) solutions and human "virtual presence" (communications) solutions.

Case Study – Notional Automated Counter-Sniping System (Figure 2)

Consider the *notional* assemblage of an acoustic sensor being monitored by a human being, who in turn operates a rifle on remote control:

- If the human being is working purely from the sensor data, then it is effectively beyond-visual-range combat.
- The authorisation for the human to fire is the familiar issue of mission command, and Rules of Engagement in particular.

Now remove the human link between sensor and shooter, and replace it with a direct (electronic) link. That is, the acoustic sensor report is the shooting cue for the rifle:

- Such a system is functionally equivalent to a land mine, merely more aware.

The challenge to conceptual systems like these is, therefore, in their capacity to discriminate – *not* in their capacity for automated action.

Figure 2: Notional Automated Counter-Sniping System.

Technology Bottleneck Issues

6. *Communications and Programmability.*

   The capacity to communicate with the robot once deployed, and thus change its behaviour, is a significant driver on the balance of engineering for robot autonomy versus control by a human.

   In the absence of new physics, robot system developers will continue to rely on known communication media (electromagnetic radiation, electricity, acoustic radiation). They will take on the continuing advances in microelectronics and optics, notably in analog-digital conversion and phased array technology, but will otherwise run up against fundamental physical limits (speed-of-light, horizon line-of-sight, occlusion).

   Round-trip delays will thus limit the feasible range for effective remote-control (zero or low autonomy) robots. Moreover, the data flows required for "human virtual presence" will not be trivially achieved. The combination of compression and simulation technologies may, however, provide human operators a sufficient feeling of presence; if not, robot system designers will have to provide autonomy to the robot to make up for the gaps in human input.

7. *Navigation within physical environment.*

   The capacity for a robot to locate itself within the physical environment, in both absolute and relative terms, impacts on the acceptability of direct and collateral effects.

   Where possible, robot system designers will continue to simplify the demands on awareness. This can be achieved physically (structuring the environment) or by information means (supplying navigation cues readily detected by machine sensors, pre-mapping the environment). These measures, however, cannot be universally applied, urban terrain being a key example.

   Present-day technology is sufficient to gather appropriate depth map data. The challenge lies in the accumulation of depth data as the robot moves. The problem is of combinatorial complexity, and thus will not be solved by ongoing advances in conventional computing. The intrinsically parallel computations enabled by DNA or quantum computing may open options, over and above heuristic insights made by robot system designers.

8. *Monitoring of physical status.*

   The capacity of a robot to monitor its physical status weighs into the need or otherwise for human monitoring or intervention.

   In the near to medium term future, this issue will be eased by ongoing progress in microelectronics/optics and electronic computing. Significant improvements could also arise from smart materials and grid computing.

9. *Location of other entities in physical environment.*

   The capacity of a robot to locate other entities in the physical environment, and potentially react to or interact with them, impacts on the acceptability of direct and collateral effects.

   The issues that hold for robot navigation carry forward, compounded by the dynamic element. Where possible, robot system designers will tag entities by means readily

detected by machine (electronic) means, however, the battlespace will include neutrals that cannot be readily tagged, and hostiles actively avoiding detection. The scope of the problem thus encompasses the space of sensors and the exploitation of sensor data.

In the near to medium term future, progress will come with the general push to improve battlespace management (notably airspace and friendly fire deconfliction). Conversely, robots will need to be able to report their location and intended movements, at tempos demanded by battlespace management systems. This may compromise robot freedom of movement, and will add to communication loads.

10. *Target Modelling.*

The robot's capacity to model targets has direct and collateral effects, particularly when the robot's action generates a lethal effect.

To date, technology has enabled approaches based on "Engage Unless Friendly" and "Compare with Supplied Model". For conventional militaries, environmental drivers combined with the potential from communications technology may orient robot system designers to the latter approach.

A third approach, "Training by Similarity", will continue to be an ongoing goal of artificial intelligence research. This research involves the search for workable processes, and has not progressed to the implementation and refinement of processes that are known to work, so no predictions can be made as to when success may occur. However, the intrinsically parallel computations enabled by DNA or quantum computing may open options, over and above ongoing improvements in conventional computing hardware and scientific software.

Case Study – Pilot Situation Awareness – Predator vs Joint Strike Fighter (Figure 3)

The Predator UAV can fly a preset course for a reconnaissance mission, though the pilot can take manual control. Pilots have likened flying the Predator in this way to "flying an airplane while looking through a straw.", suggesting that "virtual presence" has a long way to go. However, overall awareness of the battlespace can be better than in contemporary aircraft, from provision of networked data.

The fusion of data for the pilot is a significant proportion of the Joint Strike Fighter project. Data from onboard and offboard sensors is fused into a single, overall picture of the battlespace, while the integrated helmet projects an image onto his retina so that navigation, targetting and terrain information appear to float in space, keyed to the direction he/she is looking in.

Pilot situation awareness for Predator and JSF are thus convergent, in terms of bringing electronically-sensed data to the human. The divergences are in:

- Control of the air vehicle, given the available communications (round-trip delay).
- The value of data directly acquired by human senses, instead of those on the aircraft ("Mark I Eyeball").

Both points are open to advances in technology.

Figure 3: Predator Remote Pilot Station, Joint Strike Fighter Cockpit Simulator.

Issues for Force Development

11. *Strategic Impact*

Given the precedents in concept development, and the known bottlenecks and progress in technology, robotics has *passed* the point of being a new strategic threat, to one that *broadens* the threat at the operational and tactical level. The key feature is *comodification*, enabling different actors to utilise formerly-specialised technology. The threat space from autonomous systems thus builds on advances and comodification of enabling technologies, notably including: insertion into space/orbit, civilian communication networks, and computer hardware and software.

12. *Impact on ISTAR*

If robots are expected to operate at high awareness, then they become high-demand customers of ISTAR support. This can already been seen in the information demands to support next-generation precision-guided munitions.

The potential for robots to be high-value contributors to the overall ISTAR system is already recognised, again assuming communications support.

Case Study – V-1, Tomahawk, Joint Air-to-Surface Standoff Munition (Table 4)

The progression from V-1 through Tomahawk to JASSM highlights the demands on ISTAR and communications to support robots, under increasing demands for precision and flexibility of use. It also shows how "electronic tagging" of the environment can simplify the ISTAR demand; for instance, GPS massively simplifies navigation, but presupposes that the GPS constellation is in place and operating.

Table 4: Case Studies – V-1, Tomahawk, Joint Air-to-Surface Standoff Munition.

System	Navigation	Retarget?	ISTAR + Communications Demand
V-1	Constant azimuth, timed distance.	No.	Geographic coordinates of target, surveyed launch site.
Tomahawk	Terrain Comparison, Digital Scene Matching	No.	Terrain height profile to target area, digital scene of target.
Tomahawk (with GPS)	GPS, Digital Scene Matching	No.	Assumes GPS constellation, digital scene of target.
JASSM	GPS, 3D Model Comparison	Yes.	Assumes GPS constellation, 3D model of target. Communications link to missile.

13. *Demand for Communications Support*

    Robot operations, particularly those at low autonomy and at extended ranges, will add to the demand for communications support. The chronic shortage in satellite time will be a problem, and will not be solved without substantially cheaper access to space and orbit. Relay aircraft could be used, but it is noted that suitable relay aircraft are valuable assets and may be on other missions. Unconventional forces could leverage mobile phone networks; conventional forces need to at least be aware of this potential, with key issues noted in the next point.

14. *Thinking on Expeditionary Forces*

    A deployed robot is essentially an expeditionary force in microcosm, with all the support issues that it implies. As a case in point, a robot designed for control through a mobile phone network assumes deployment within a region where access to and security within a friendly phone network can be assured.

Case Study – Mobile Phone Bombs

Mobile phones have been used by unconventional (terrorist) forces as remotely-activated bomb triggers. Notable observations:

- The unconventional force leveraging its adversary's communication network. In particular, the unconventional force is parasitically benefiting from the confidence built into the network towards its civilian application.
- A conventional warfighting counter might be to suppress the networks. However, for peacekeeping this would be counter-productive, in that civilian communications is part of (re)establishing normal conditions.

The further application of civilian communication networks to robot control is thus neither avoidable nor something that can be easily suppressed.

15. Arms Control Conventions

The consequences of a robot's actions are a valid dimension for defining valid robot use, as much as the capacity of its technology. The particular case studies of the Hague Convention VIII and Ottawa Convention are revealing, in dealing with robot weapons (mines) in different ways; it is argued that in targeting consequences, the Hague Convention VIII will be more resilient and lasting than the Ottawa Convention. Future arms control conventions might similarly seek to control direct and collateral effects of weapon systems, both in and post conflict, rather than the capacity for such weapon systems to automatically engage a target.

Case Study – Hague Convention VIII and Ottawa Convention (Table 5)

The Hague Convention VIII sought to control the consequences of robot failure, for instance, in requiring automatic safing if becoming untethered. The Ottawa Convention, by contrast, makes its ban in the dimension of autonomy, in banning systems that trigger on human presence. As a result, the Ottawa Convention may make it difficult for signatories to deploy weapon systems that meet the humanitarian intent, but that are blocked from being autonomous and aware.

Table 5: Hague Convention VIII and Ottawa Convention Compared.

Convention	Banned (Sample)	Comments
Hague VIII (automatic submarine contact mines)	Article 1. It is forbidden -- 1. To lay unanchored automatic contact mines, except when they are so constructed as to become harmless one hour at most after the person who laid them ceases to control them; 2. To lay anchored automatic contact mines which do not become harmless as soon as they have broken loose from their moorings; …	Directly targets *un*controlled explosive material. Other articles call on signatories to clear waterways of unexploded ordnance post-conflict.
Ottawa (anti-personnel mines)	"Anti-personnel mine" means a mine designed to be exploded by the presence, proximity or contact of a person and that will incapacitate, injure or kill one or more persons. …	Black-or-white definition of triggering "by presence, proximity or contact" may block future weapon systems with better discrimination.

3. Summary

This paper summarised the study [2] on the potential impact of robotics technology on near- to medium- term future warfighting. From a model of autonomous systems that centred on deployment by, and input from, a human being, the critical aspect of *autonomous situation awareness* was captured in linked but distinct continuums of:

1. *Autonomy*, measured by the time between references to a human being for input.
2. *Awareness*, measured by the system's usage of information about its environment.
3. *Situation*, driven primarily by the severity of consequences of the system making decisions and taking action.

The central result is that it is not a question of whether a system "is" autonomous or "has" awareness, but whether the system has *sufficient* awareness to be *sufficiently* autonomous for the situation at hand. Historical review identified cases where "dumb" technologies with low awareness had been deployed at high autonomy, while "smart" technologies with high awareness had been held at low autonomy. Historical experience also suggests strong precedents for concept development, notably from mine warfare, beyond visual range combat and mission command.

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16. DELIBERATE ANNOUNCEMENT

No Limitations

17. CITATION IN OTHER DOCUMENTS Yes

18. DEFTEST DESCRIPTORS

automation, futures analysis, robotics, situational awareness.

19. ABSTRACT
This study aims to clarify and capture the nature of electronic situational awareness and its interface with electro/mechanical systems. It argues that "autonomous situation awareness" is about the sufficiency of awareness for autonomy in the situation at hand. The approach is calibrated through historical case studies, and the study then considers the potential from near to mid term technology.